TEMPEST-D: Temporal Experiment for Storms and Tropical Systems Demonstration Mission

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Matthew Pallas, Doug Laczkowski, Nancy Gaytan and Austin Bullard, *Blue Canyon Technologies*

Earth Venture Technology (EVI-2)

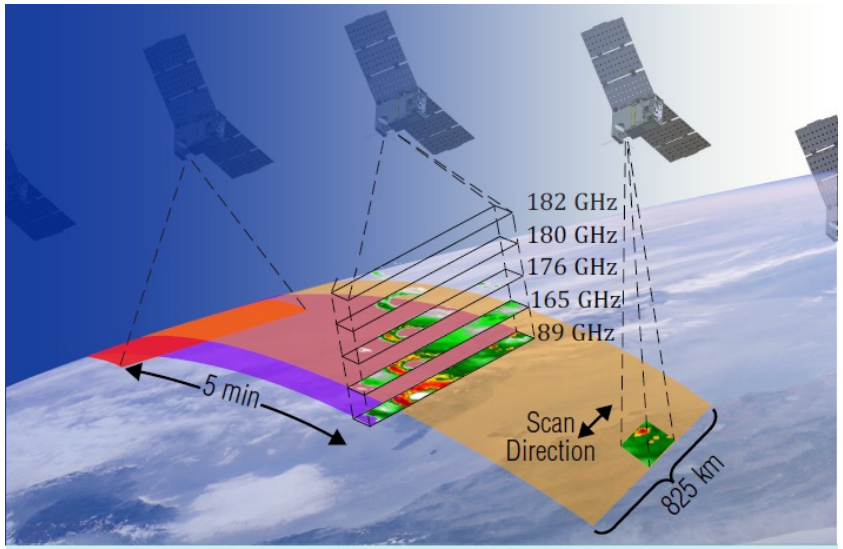
Thanks to NASA Wallops for ground comms!

Temporal Experiment for Storms and Tropical Systems (TEMPEST)

TEMPEST addresses 2017 National Academies Earth Science Decadal Survey:

- *Why do convective storms, heavy precipitation, and clouds occur exactly when and where they do?* (Most Important Science Question W-4)
- Proposed to NASA EVI-2 in 2013 as a constellation of 5 identical 6U CubeSats to provide *temporally-resolved observations of rapidly-evolving storms* every 5 minutes for up to 30 minutes.
- Chosen as NASA Earth Venture Technology Demonstration mission and delivered a 6U CubeSat with multi-channel millimeter-wave radiometer for launch less than 2 years after PDR.

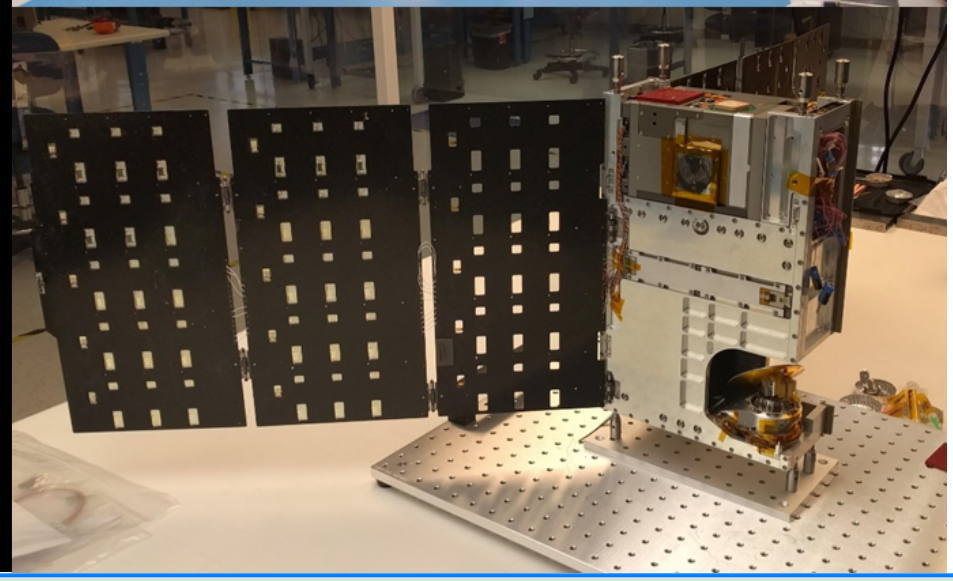
- Launched by Orbital ATK from NASA Wallops to ISS on May 21, 2018.
- Deployed into orbit by Nanoracks on July 13, 2018.



5 identical 6U small sats, each with an identical 5-channel radiometer, flying 5 minutes apart

NOAA Advanced Technology Microwave Sounder (ATMS)
75 kg, 100 W, $$$$

TEMPEST-D
3.8 kg, 6.5 W, $



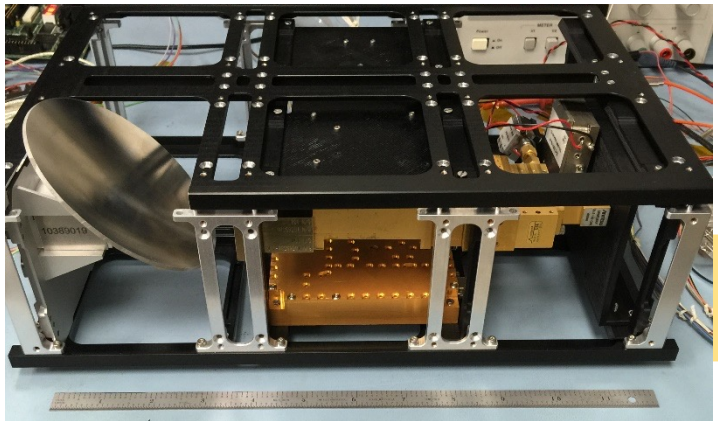
TEMPEST-D Team and Heritage Reflect Over a Decade of Investment in Earth Science Technology Development

TEMPEST-D Team (L to R): Rudy Bendig, Mary Soria, Sharmila Padmanabhan, Ann Batchelor, Bob Bauer (ESTO), Steven Reising and Cate Heneghan

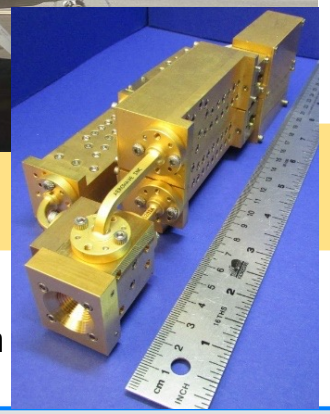
Sustained investment by JPL and ESTO led to TEMPEST proposal to NASA EVI-2 in 2013 (CSU/JPL)

NASA ESD created Earth Venture Tech Program in 2014

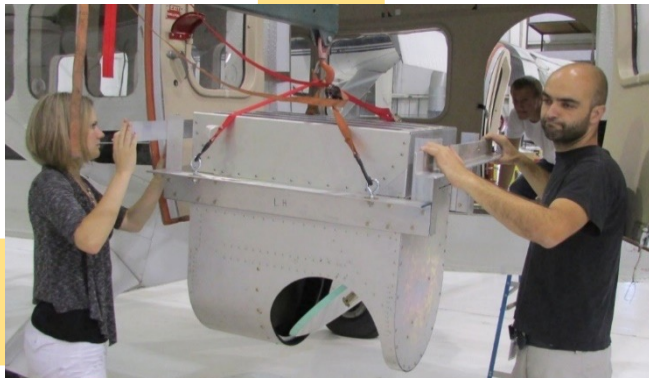
TEMPEST-D Instrument Team (L to R): Todd Gaier, Heather Lim, Alan Tanner, Sharmila Padmanabhan, Rudy Bendig and Boon Lim



Microwave Atmospheric Sounder on CubeSat (MASC, JPL R&TD)

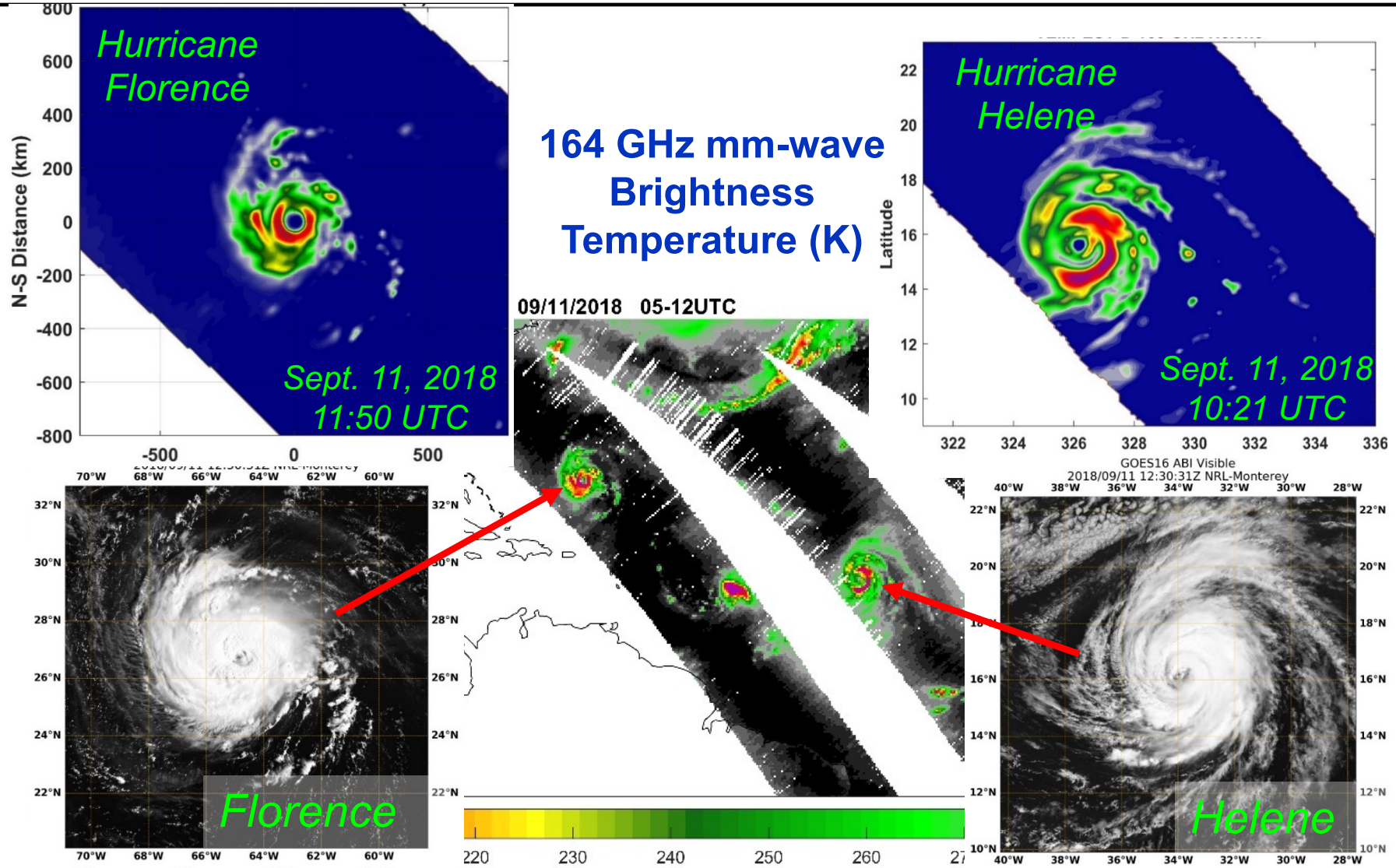


Also led to HRMR on Sentinel-6 Michael Freilich

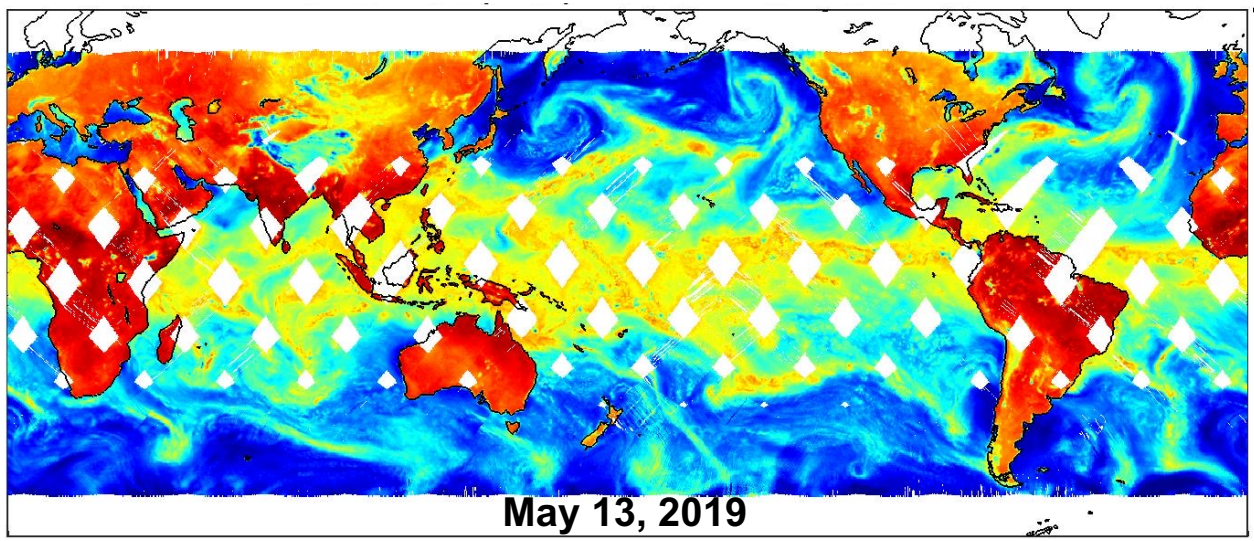


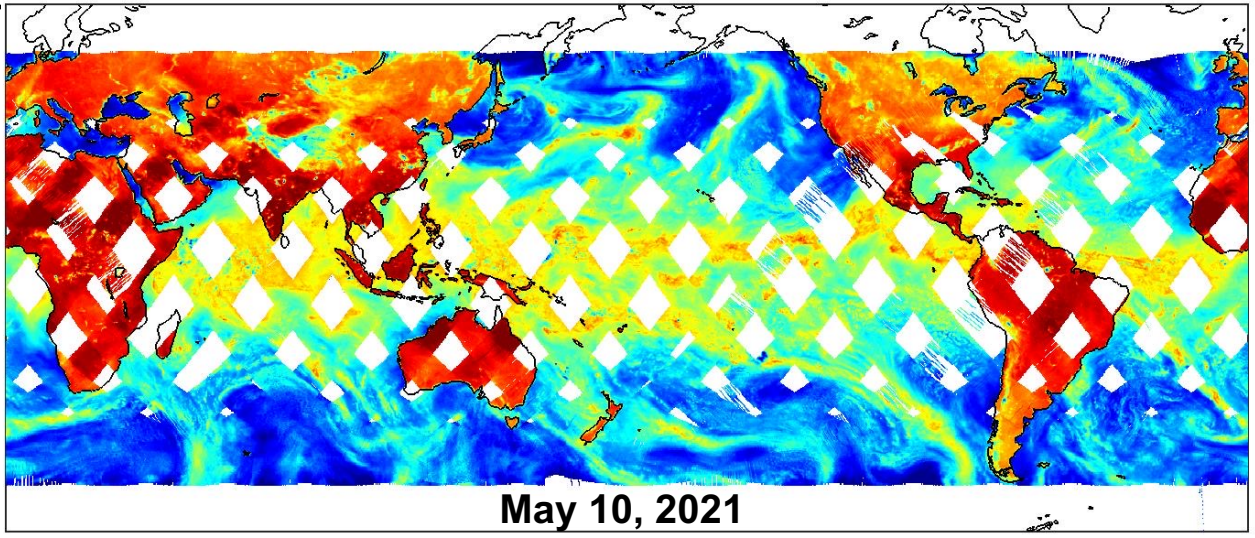
High-frequency Airborne Microwave and Millimeter-wave Radiometer (HAMMR IIP, NASA ESTO, CSU/JPL)

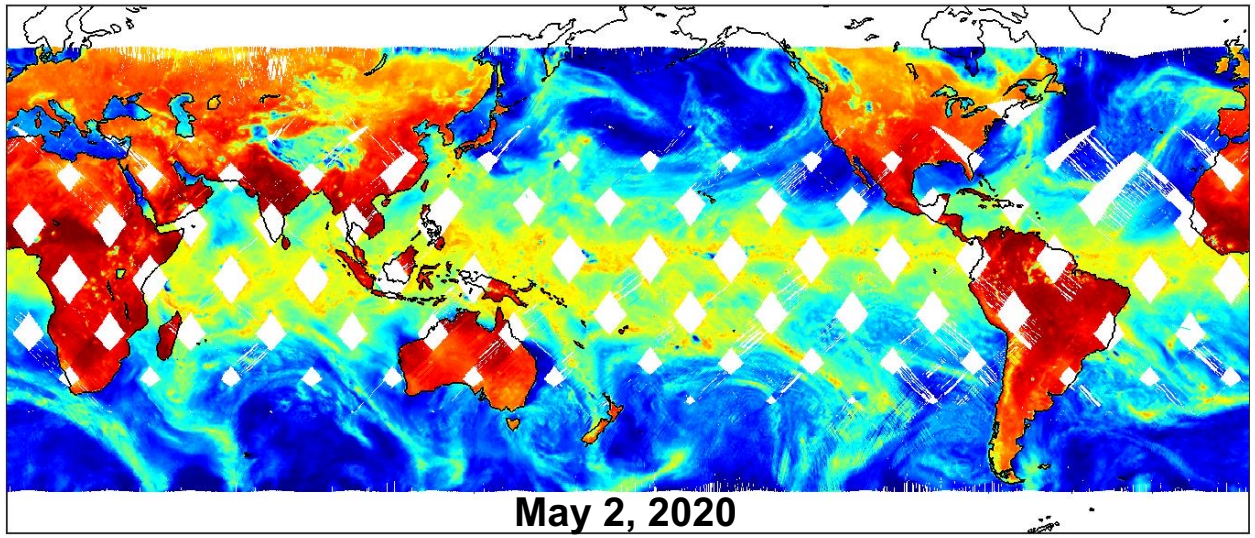
TEMPEST-D First Full Orbits on Sept. 11, 2018

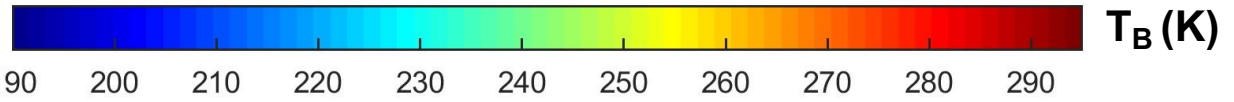


TEMPEST-D Venture Tech Mission: Observing Global Brightness Temperatures for the Past 3 Years







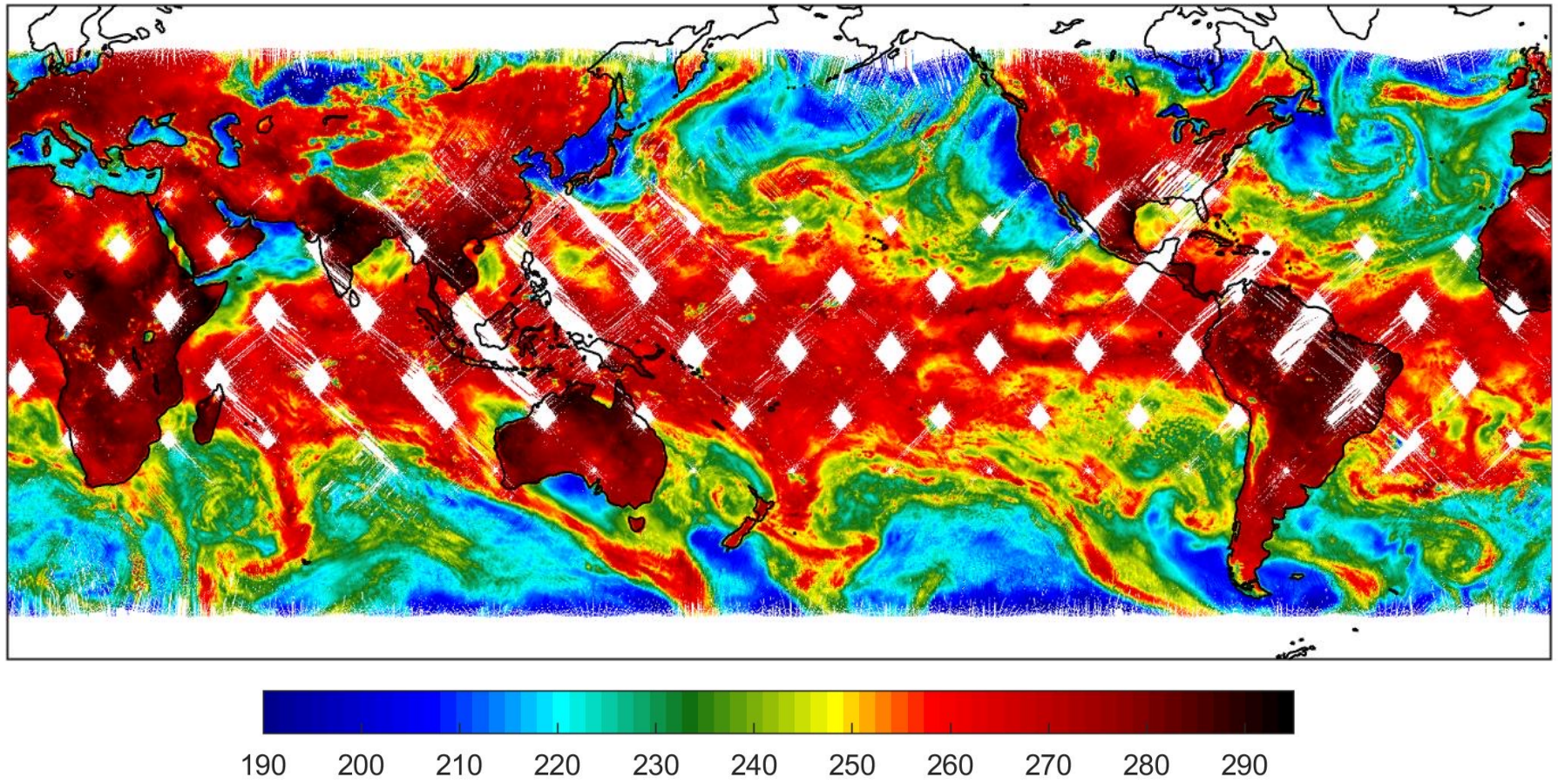


87 GHz brightness temperatures for May 2019, May 2020 and May 2021.

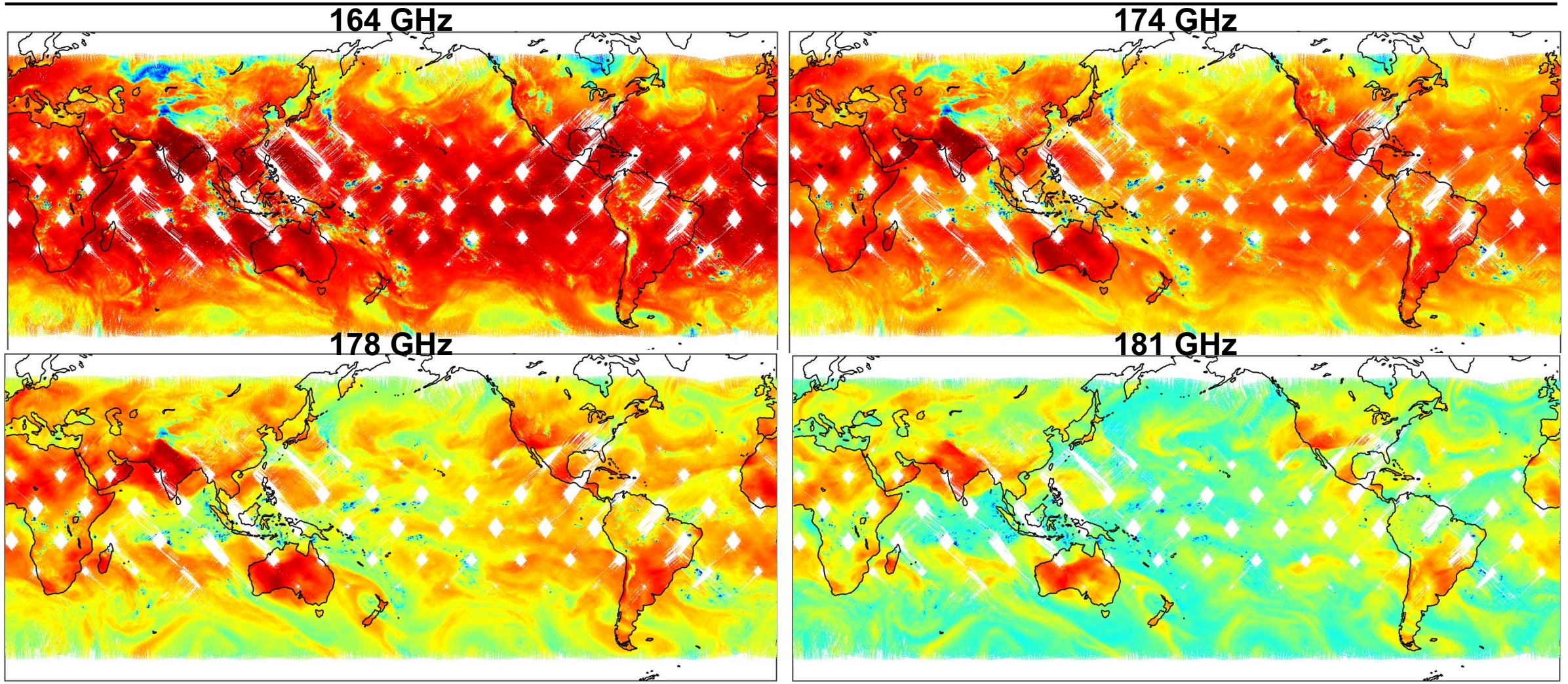
TEMPEST-D Venture Tech Mission: Producing Global Atmospheric Science Data After Nearly 3 Years on Orbit

- TEMPEST-D multi-channel mm-wave radiometer was in hibernation on orbit for 6 months due to downtime at NASA Wallops for repair of the UHF antenna system.
- These global Earth observations from the TEMPEST-D CubeSat were made only 9 hours after the instrument was turned on.
- TEMPEST-D instrument performance after 6 months of hibernation in space is the same as before.

TEMPEST-D 87 GHz Brightness Temperatures (K) Observed on March 31, 2021



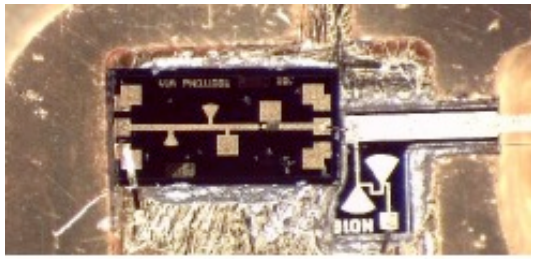
TEMPEST-D Venture Tech Mission: Producing Global Atmospheric Science Data After Nearly 3 Years on Orbit

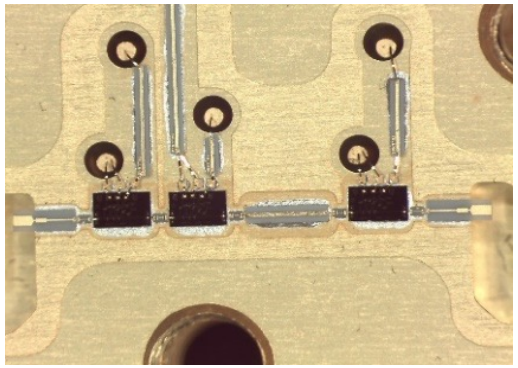


TEMPEST-D Observations on March 31, 2021

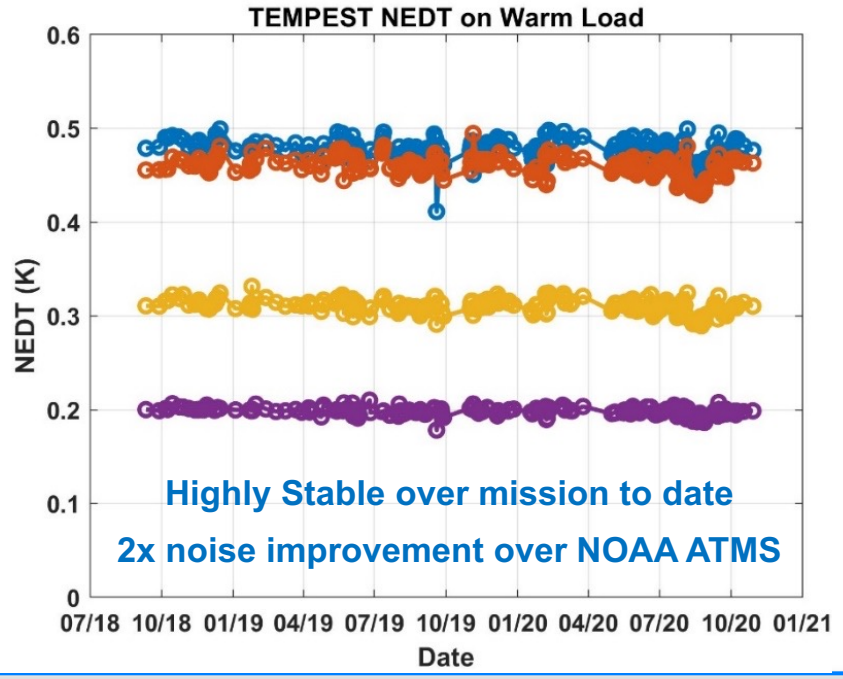
TEMPEST-D CubeSat Producing Well-Calibrated Atmospheric Science Data for Nearly 3 Years on Orbit

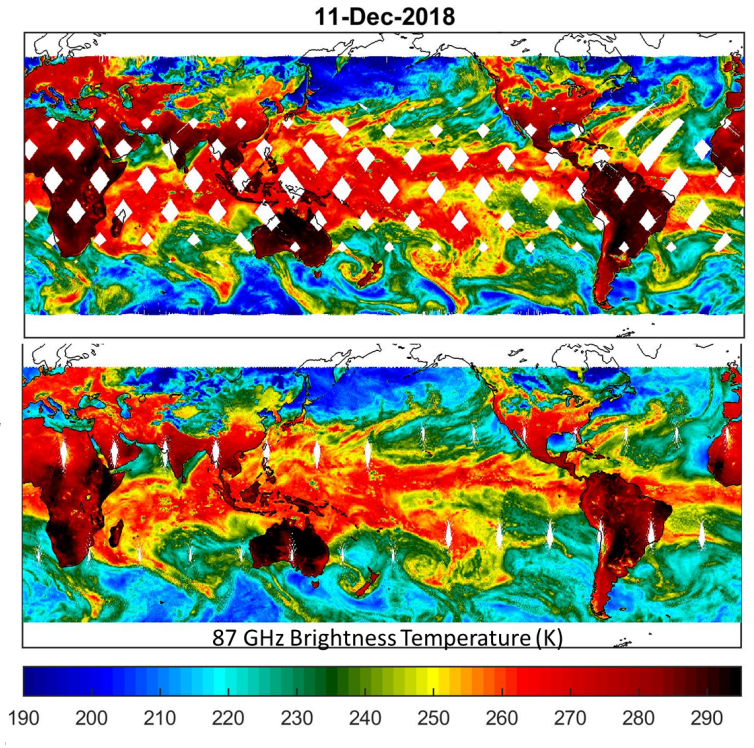
On-orbit demonstration of new InP HEMT Low Noise Amplifier Technology





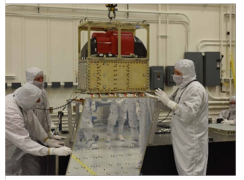
Padmanabhan et al., TGRS, 2020.





TEMPEST-D

3.8kg, 6.5W, $

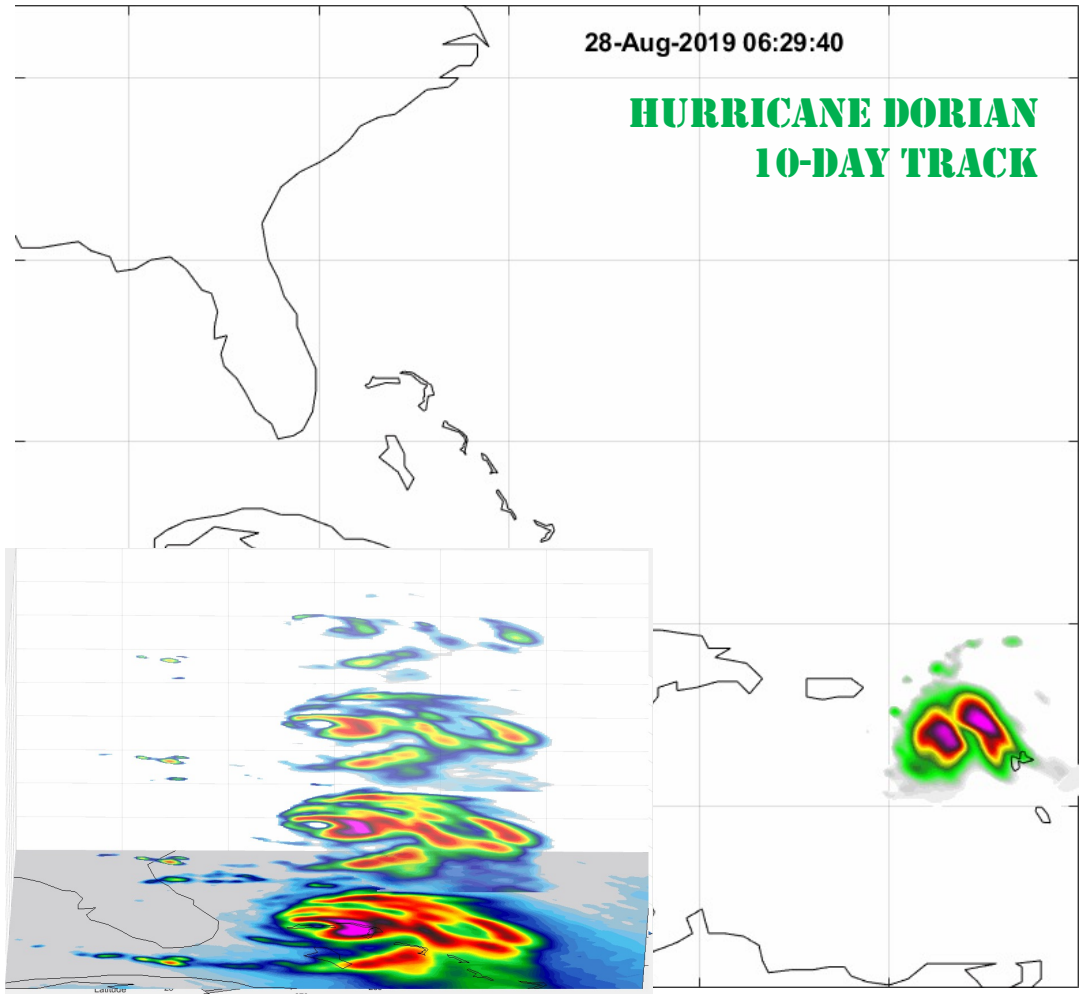


NOAA Advanced Technology Microwave Sounder (ATMS)

75kg, 100W, $$$$

- TEMPEST-D calibration demonstrated to be equivalent to operational sensors (*Berg et al., TGRS, 2020*)
- Radiometer accuracy, precision and stability all rock solid after nearly three years on orbit
- Extended mission provides risk reduction for future operational missions

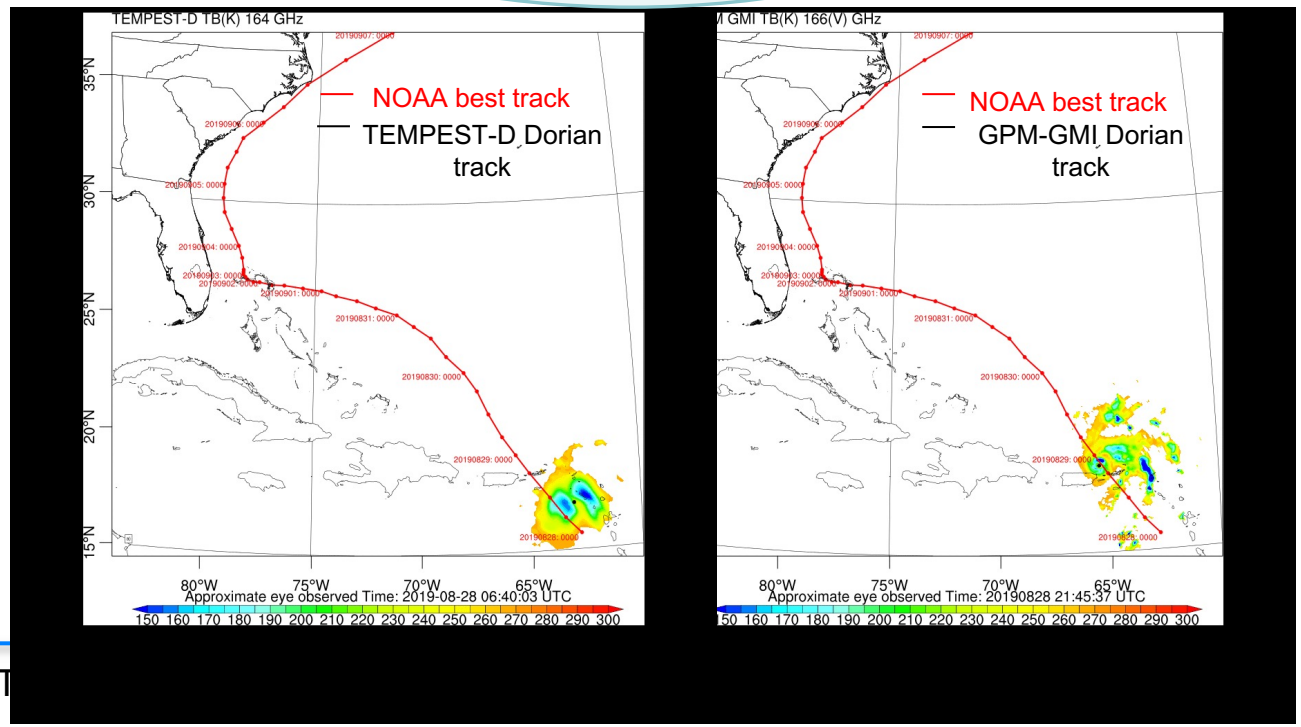
TEMPEST-D CubeSat Mission: Observing Hurricanes, Tropical Cyclones, Oceanic and Continental Storms for Nearly 3 Years



Calibrated TEMPEST-D data are publicly available!

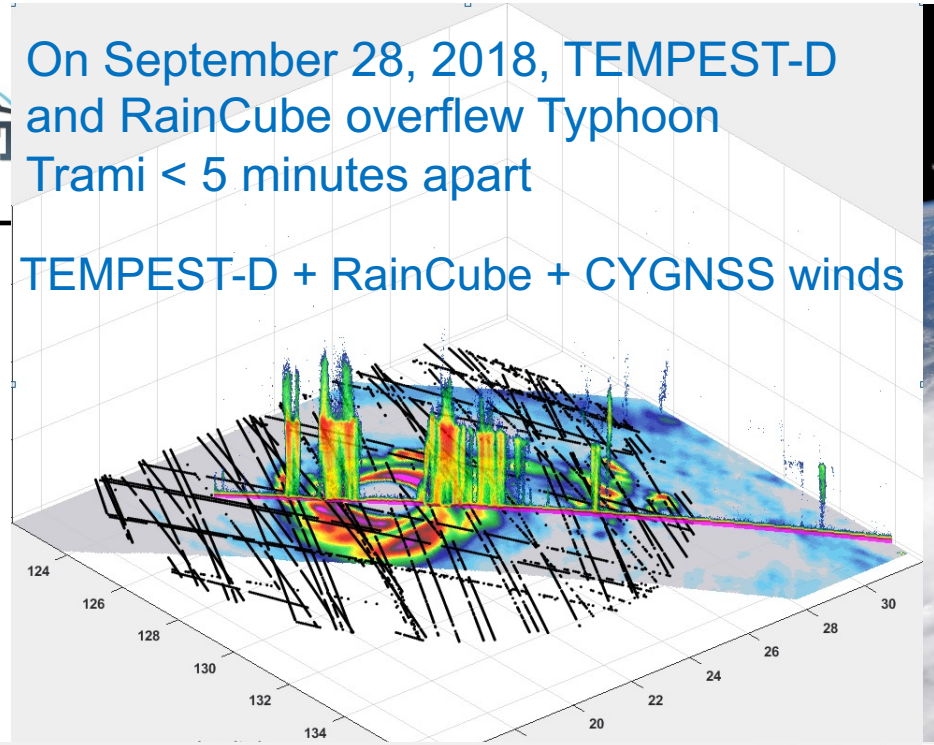
https://tempest.colostate.edu/data

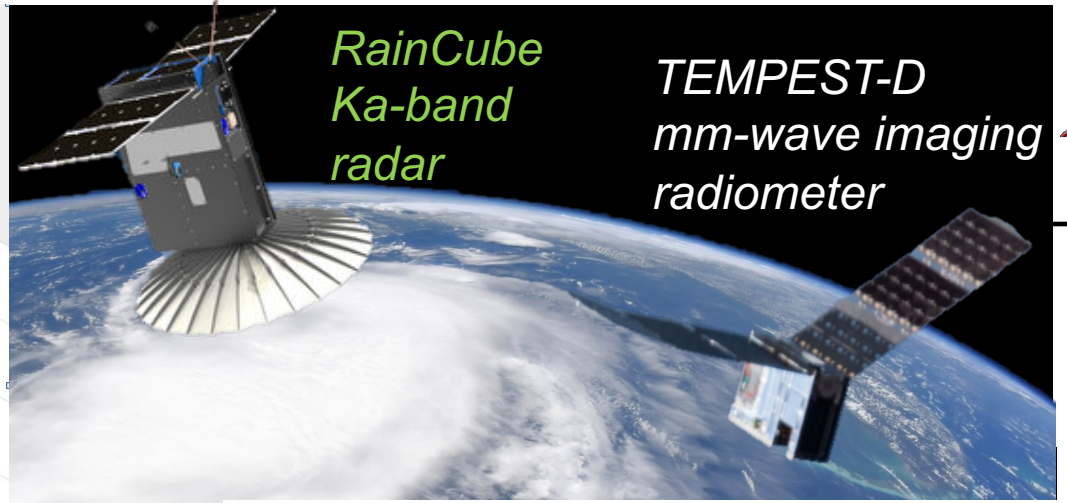
TEMPEST-D data have been downloaded by 41 institutions in 12 countries on 4 continents.

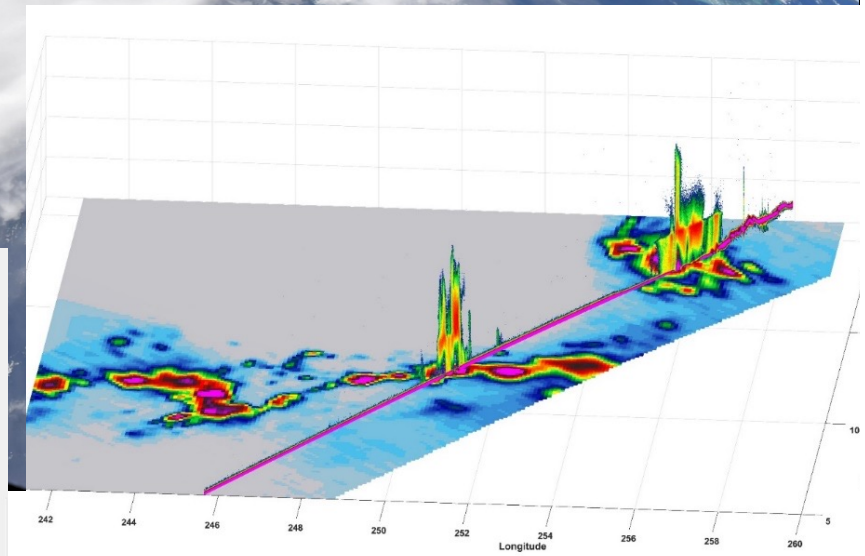


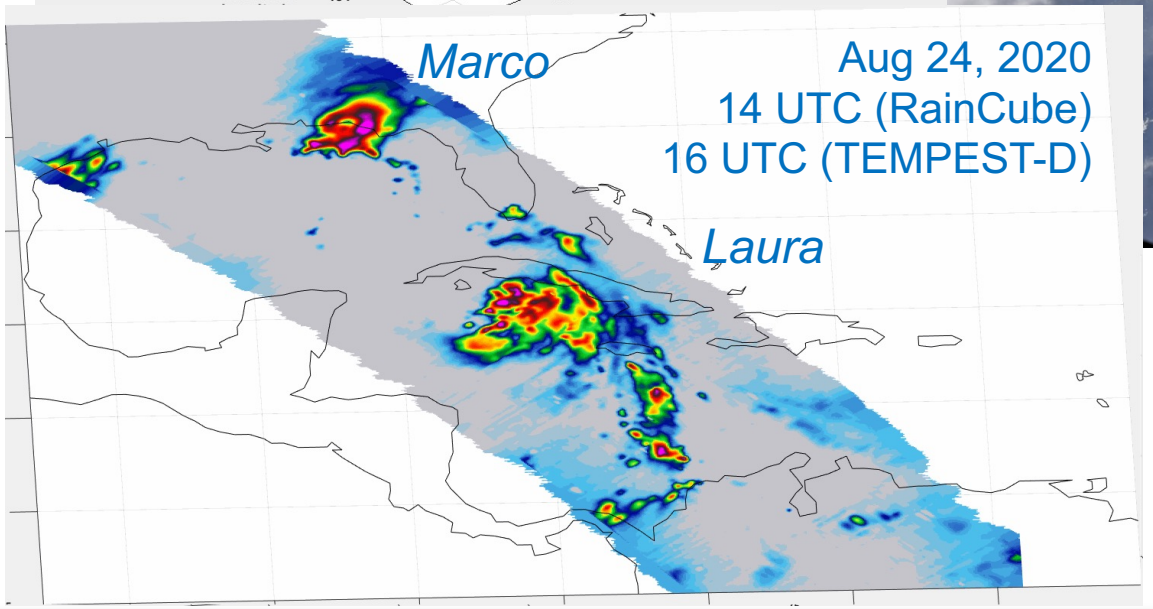
On September 28, 2018, TEMPEST-D and RainCube overflew Typhoon Trami < 5 minutes apart

TEMPEST-D + RainCube + CYGNSS winds

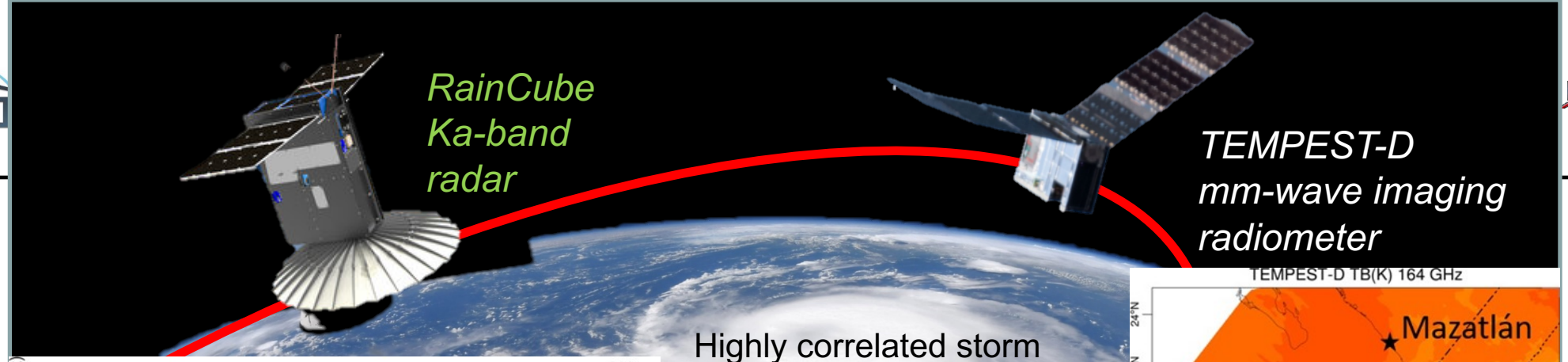




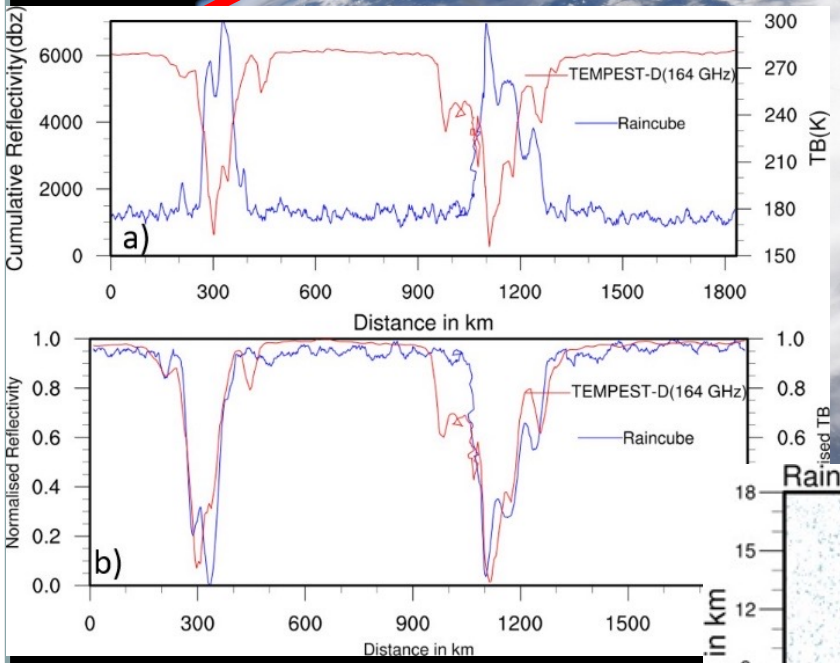


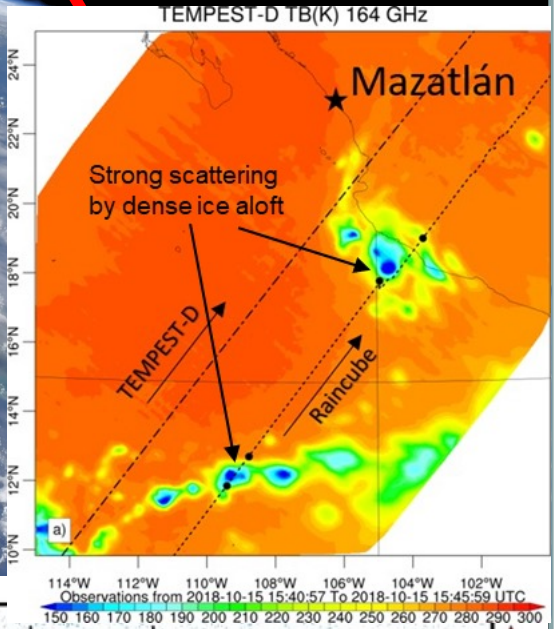


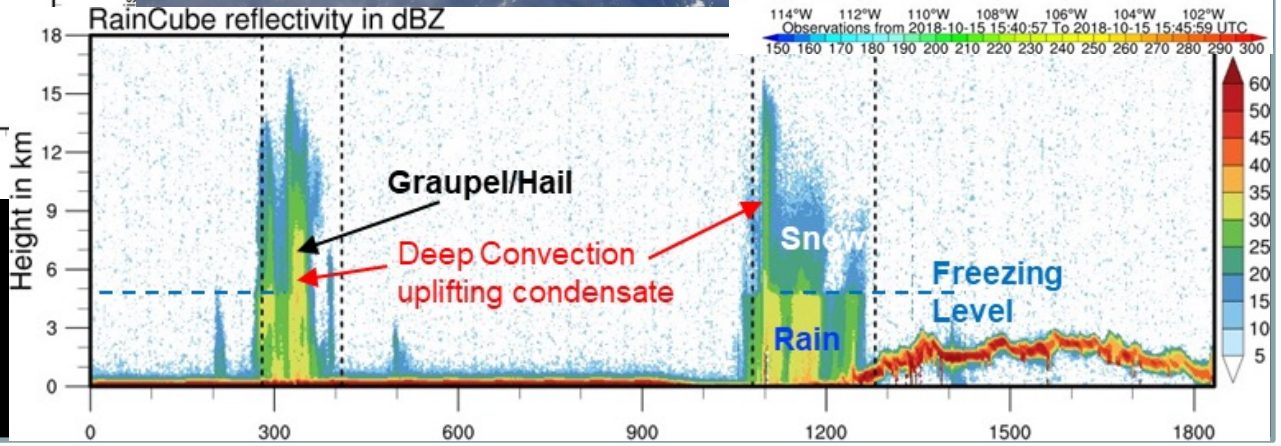
Oct 15, 2018 at 15:25 UTC
Orographic precipitation off Mexican coast



Highly correlated storm measurements from RainCube radar and TEMPEST-D radiometer over Texas, Mexico and Pacific Ocean



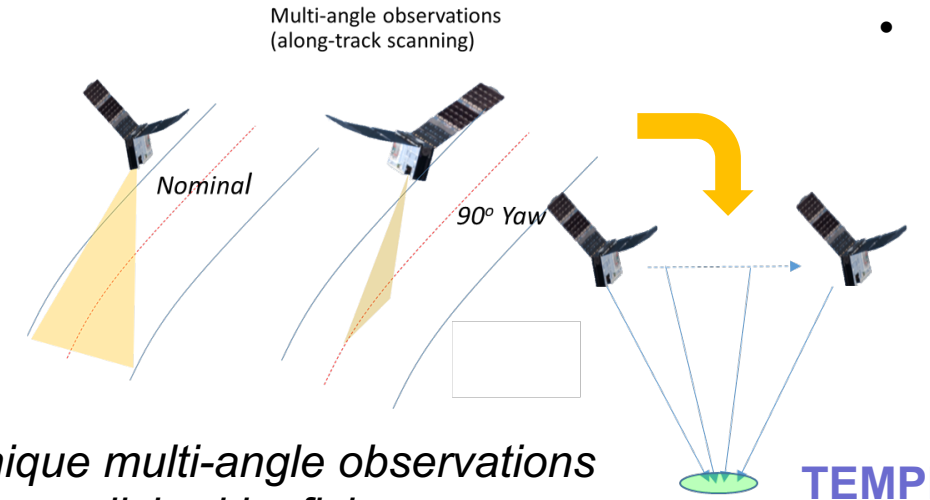




Correlation coefficient between TEMPEST-D TB and RainCube Reflectivity: > 0.90

V. Chandrasekar, C. Radhakrishan, S. C. Reising, W. Berg, S. T. Brown, S. Tanelli, O. Sy and G. F. Sacco, *accepted for Proc. IGARSS 2021*.

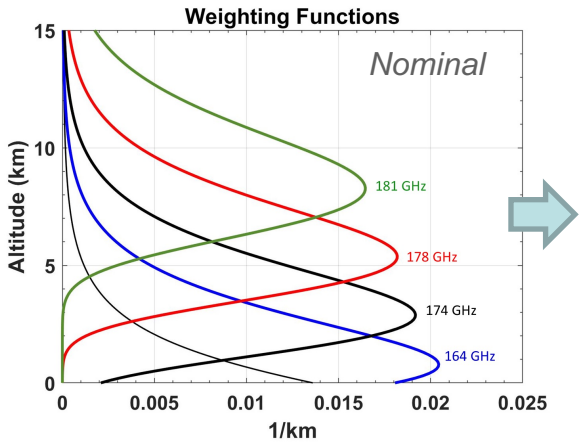
Unique Observations Demonstrated by TEMPEST-D

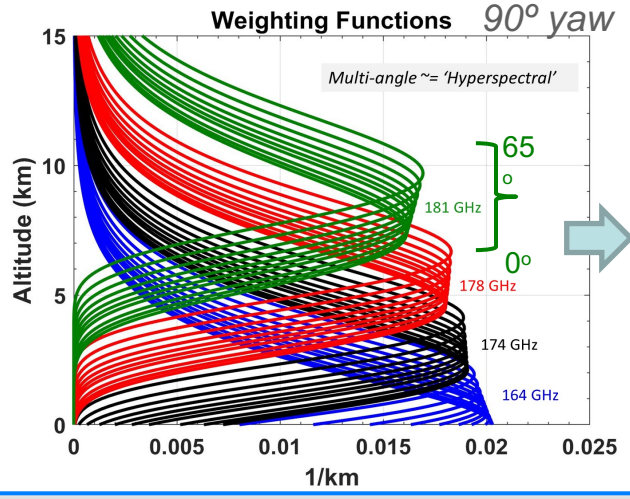


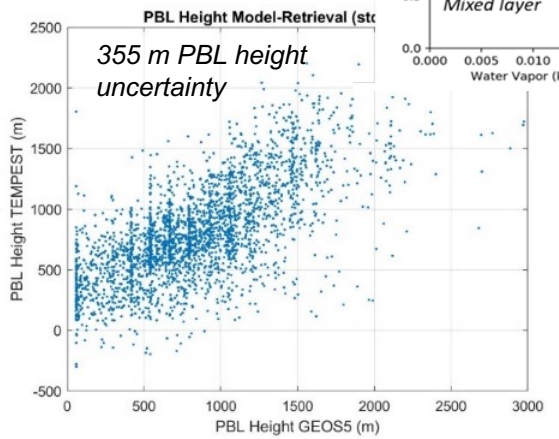
Unique multi-angle observations accomplished by flying TEMPEST-D yawed by 90º

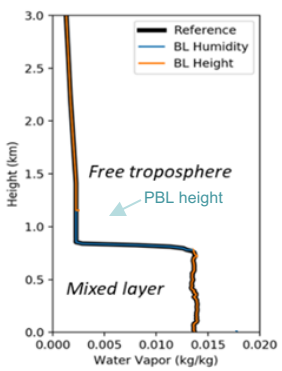
- Multi-angle sounding improves vertical sampling through troposphere, analogous to a “hyperspectral” sounder
  - A promising application is improving measurement capability in planetary boundary layer (PBL)
  - Also enables uncertainty quantification for time resolved measurement concepts

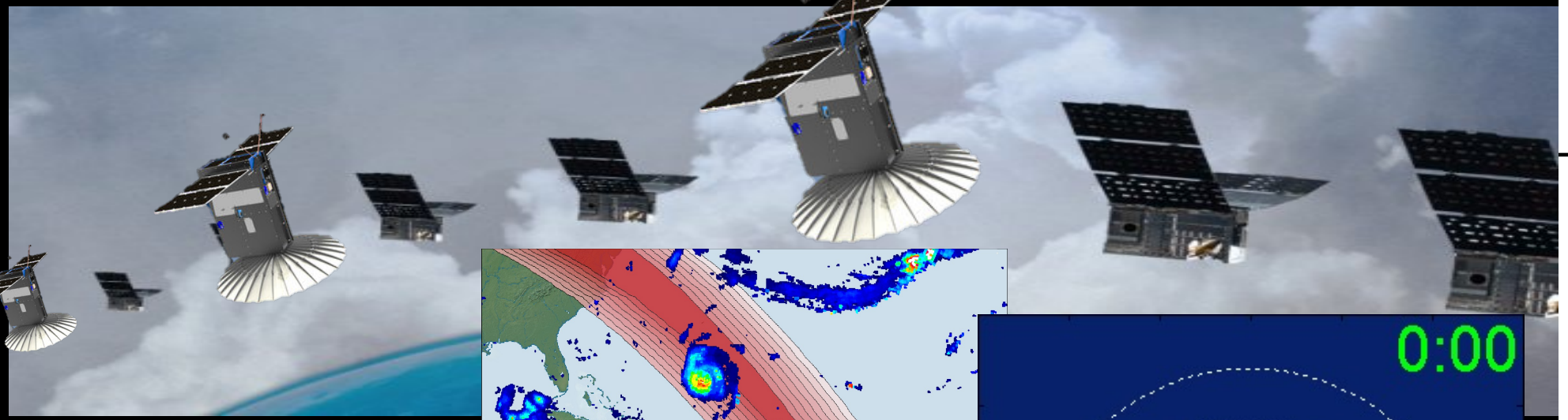
TEMPEST-D allows testing these new concepts with satellite data for the first time

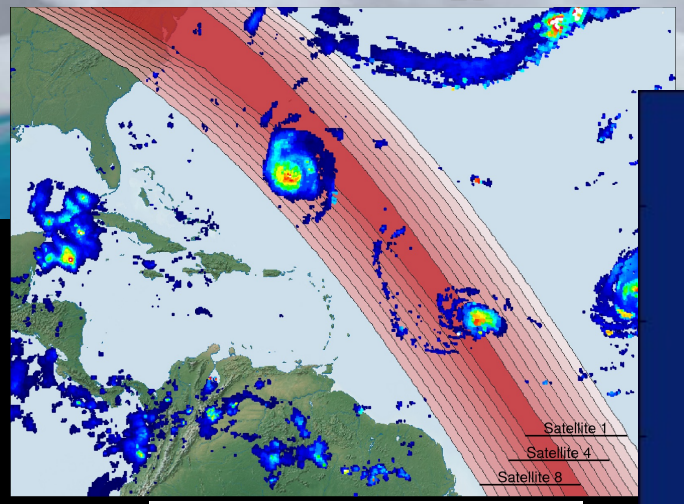


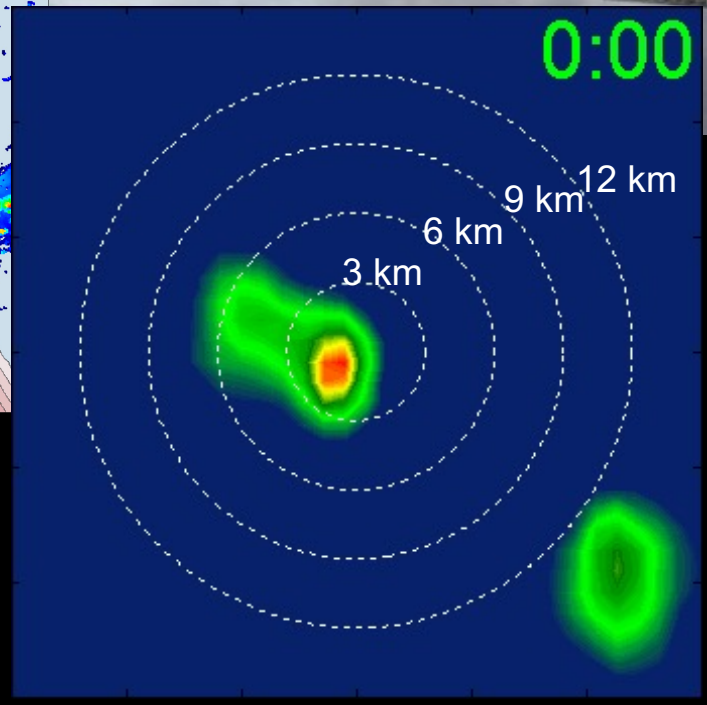






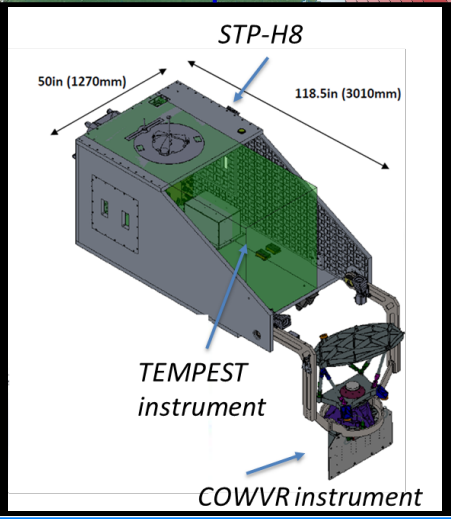






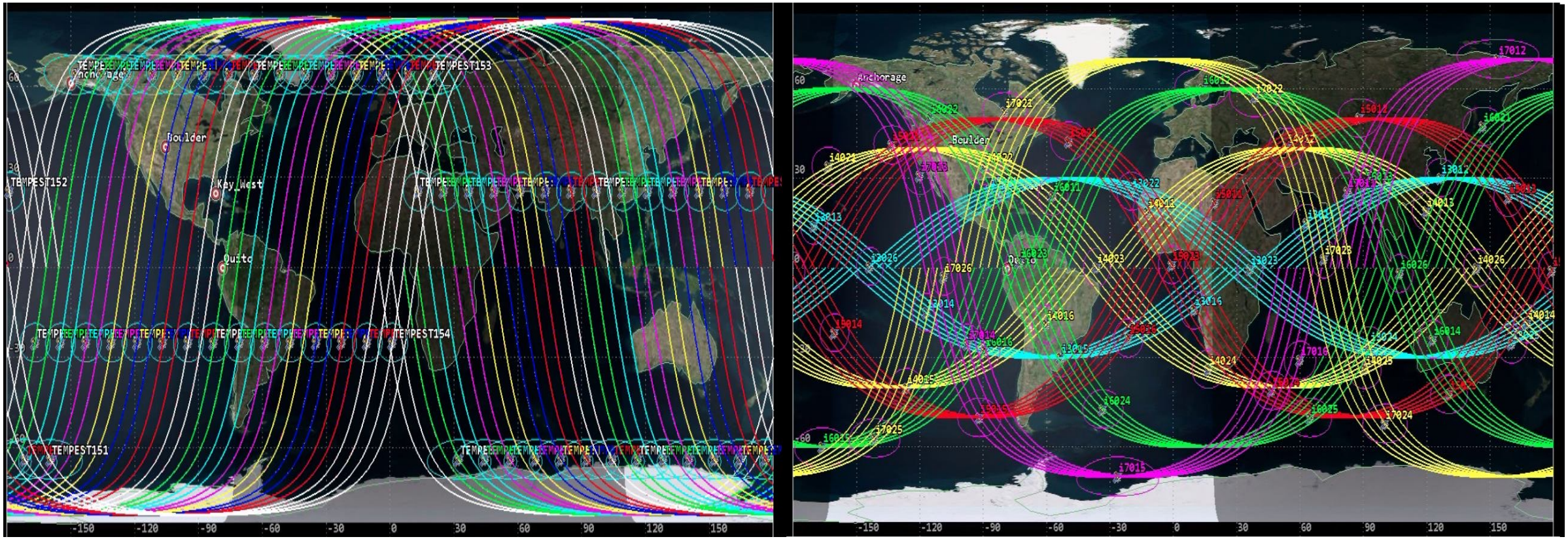
TEMPEST-D and RainCube technology enable new science mission concepts

- Constellations for rapid revisit
- Combined complementary measurements
- Available for future EV-M and EV-I opportunities



TEMPEST spare sensor will fly on ISS with COWVR for STP-H8 mission in December 2021

Design of CubeSat Microwave Sounder Constellations using 60 Satellites at 550 km Altitude

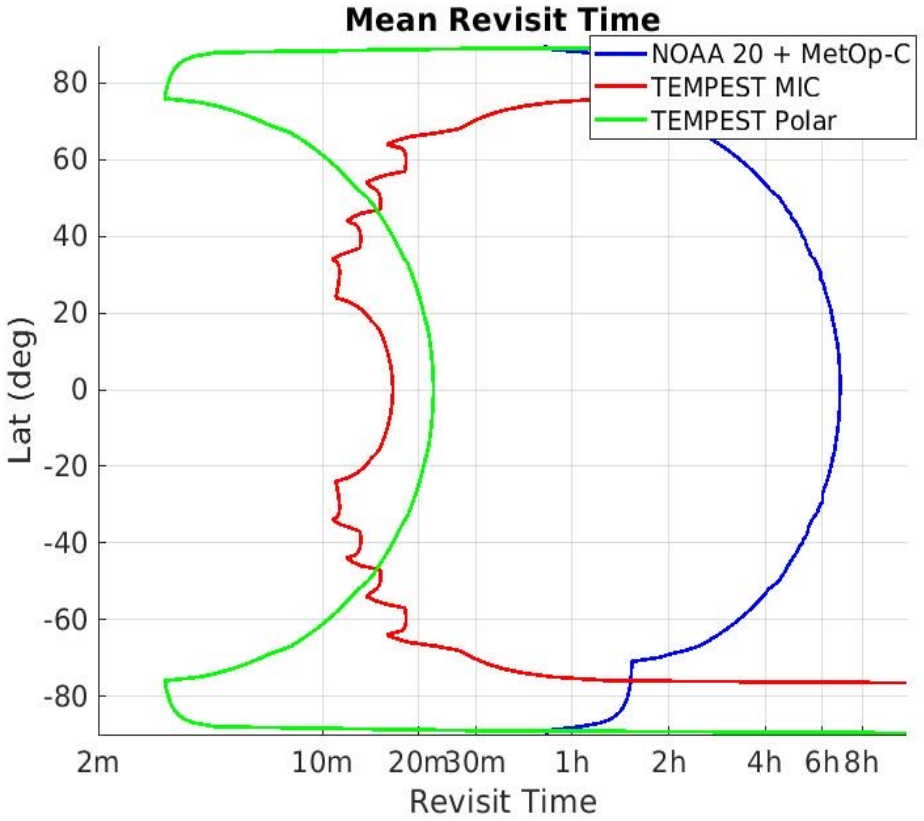


(a) (b)

Simulated ground tracks of (a) TEMPEST Polar Constellation and (b) TEMPEST Multi-Inclination Constellation (MIC) over a single orbital period (approximately 95 minutes).

Mean Revisit Time of CubeSat Microwave Constellations Compared to Current Operational Sounders

- TEMPEST Polar Constellation: all sun-synchronous
- TEMPEST Multi-Inclination Constellation: 30º, 40º, 50º, 60º and 70º

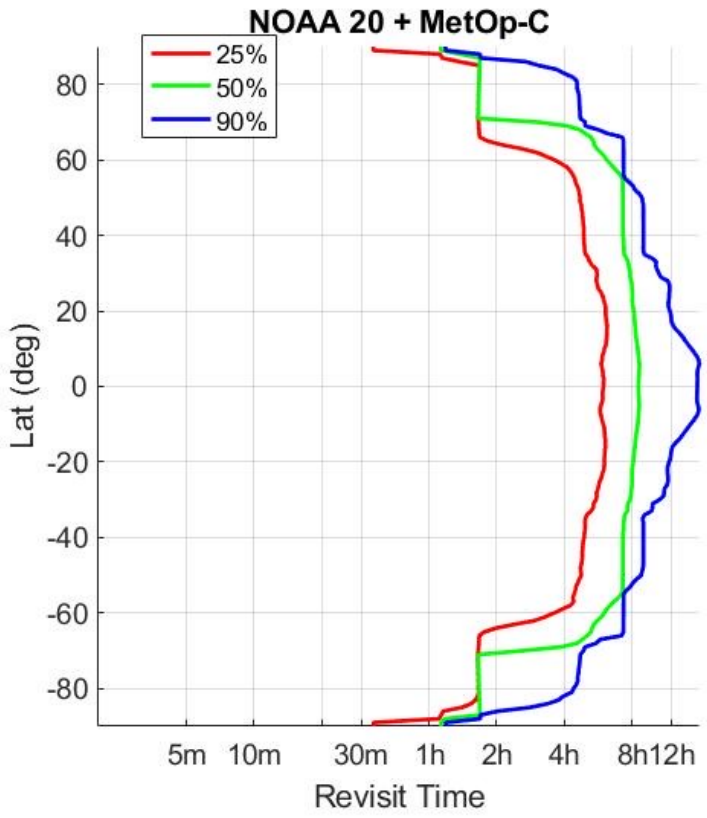


Desired revisit times to capture temporal variability:

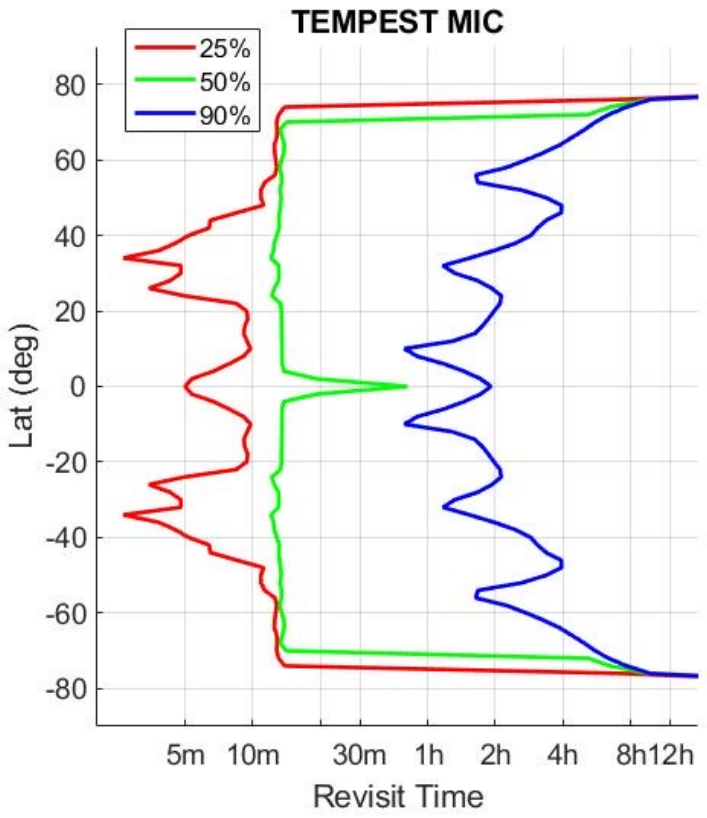
- Temperature and water vapor: order of ~1-2 hours
- Convective storm systems: order of 20-30 minutes

Mean revisit times for polar orbiter constellation (blue), TEMPEST Polar Constellation (green) and TEMPEST Multi-Inclination Constellation (red).

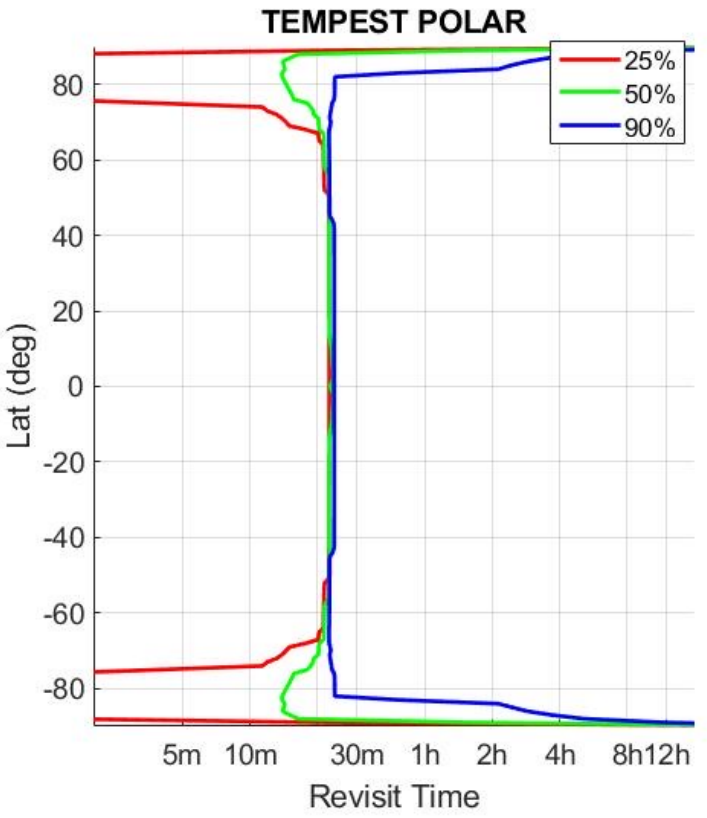
Revisit Time of CubeSat Microwave Constellations Compared to Current Operational Sounders



(a)



(b)



(c)

Revisit times of each constellation for 25, 50 and 90% of total observation time (6, 12 and approximately 21.5 hours per day, respectively).

TEMPEST-D Venture Tech Mission Contributions

- TEMPEST-D, a NASA Earth Venture Tech Demo mission, met all of its Level 1 requirements within the first 90 days of operations.
- Demonstrated rapid development cycle with delivery of CubeSat with multi-frequency millimeter-wave radiometer within 2 years after PDR.
- TEMPEST-D has significantly **exceeded requirements for calibration** accuracy and precision and has performance **comparable to much larger operational satellites**.
- TEMPEST-D radiometers are **highly stable** over the 3-year mission, with no evidence of calibration errors due to on-orbit instrument temperature.
- Demonstrated infusion of NASA ESTO-funded technology developed over more than a decade from TRL 2 (ACT-08) to TEMPEST-D tech demo/science mission at TRL 9.
- Highly-correlated complementary measurements with RainCube enable new science mission concepts for the future.
- TEMPEST spare instrument to be deployed on ISS in Dec. 2021 for 3 years.
- Future constellations have the potential to provide rapid revisit time to observe variability of temperature and water vapor as well as rapidly-evolving storms.